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THESIS

INVESTIGATING OUTFITTING DENSITY AS A COST DRIVER IN SUBMARINE CONSTRUCTION COST

by

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September 2015

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13. ABSTRACT (maximum 200 words)

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This thesis investigates the arrangement aspect of the NSRP study using outfitting density, how tightly the submarine's components are installed within a determined volume, and the correlation on production man-hours used to construct the submarine. The results of this study evaluate outfitting density and construction costs of historical submarines and find a positive correlation to aid cost estimators in determining if an outfitting density-adjusted cost estimating relationship (CER) is applicable for preparing submarine construction cost estimates.

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INVESTIGATING OUTFITTING DENSITY AS A COST DRIVER IN SUBMARINE CONSTRUCTION

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LIST OF ACRONYMS AND ABBREVIATIONS

AWE	Accepted Weight Estimate
BCC	basic construction cost
BSCI	Bureau of Ship Consolidated Index
CE	cot estimating
CER	cost estimating relationship
CF	cubic feet
CY	constant year
EB	Electric Boat
ESWBS	expanded ship work breakdown structure
ft	foot, feet, unit of length
FWR	Final Weight Report
FY	fiscal year
HVAC	heating, ventilation and air conditioning
lb	pounds, unit of weight
LT	long ton = 2,240 pounds
MBT	main ballast tank
MC	missile compartment
Mhrs	man-hours
NAVSEA	Naval Sea Systems Command
NFO	normal fuel oil
NNS	Newport News Shipbuilding
OPS	operations space
SCN	shipbuilding and conversion, Navy
SSBN	submersible ship ballistic nuclear, reference to Ballistic Missile submarines
SSN	submersible ship nuclear, reference to Fast Attack submarines
TY	then year
VLS	vertical launch system

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EXECUTIVE SUMMARY

Through the Naval Surface Warfare Center (NSWC), the National Shipbuilding Research Program (NSRP) completed a study in 1992 where the NSRP identified the top-level parameters that have an effect on the cost of naval shipbuilding. Those parameters were (1) arrangements; (2) simplicity; (3) material; (4) standardization and (5) fabrication requirements. Since 2011, the Budget Control Act has created a climate wherein cost reductions dominate the program manager's decision-making. Consequently, it is important for submarine program managers to understand the limitations of submarine cost construction estimates. A thesis by Benjamin P. Grant in June 2008, "Density as a Cost Driver in Naval Submarine Design and Procurement," suggests the potential of applying a modular outfitting density factor in the submarine cost estimating process. This thesis investigates the arrangement aspect of the NSRP study investigating outfitting density, how tightly the submarine's items are installed within a determined volume, and the possible correlation on production man-hours used to construct the submarine. The results of this study will evaluate outfitting density of historical submarines to aid Naval Sea Systems Command (NAVSEA) 05C cost estimators in determining if an outfitting density adjusted cost estimating relationship (CER) is applicable for preparing the costing position for the *Ohio* Replacement and *Virginia* class Payload Module Programs.

The NAVSEA 05C construction cost estimates use the estimated weight report for the submarine as the backbone of the estimate. CERs are applied to the estimate to convert the weight into material and labor dollars. The weight report and the cost estimate follow a very similar methodology in their development as the program progresses through the acquisition process ranging from high risk analogous estimates to low risk refined engineering estimates and extrapolated actuals.

The methodology began with the final weight estimate (FWR) of past submarine classes and extracting the outfitting weight and locations. These weights were manipulated and organized into the forward operating (OPS) compartment and aft machinery compartment. The useable volumes for the compartments per class of submarine were calculated from the Booklets of General Plans. This data was used to

develop the outfitting density for the OPS and machinery compartments for each submarine. NAVSEA 05C provided end cost and production man-hour (mhrs) return data for each submarine from the Information Management System (IMS) database. Production mhrs were divided by light ship weight (in long tons (LT)) then subtracted from the mean production mhrs/LT for the submarine fleet in Figure 1. In Figure 1, each colored shape represents each submarine class categorized by shipbuilder. The orange squares represent the *Ohio* class submarines (OH). The gray triangles represent the *Seawolf* class submarines (SW). *Los Angeles* class submarines are represented by blue shapes with shipbuilder A represented with diamonds (LA/SY A), and shipbuilder B represented with stars (LA/SY B). The *Virginia* class submarines are represented by yellow 'X' for shipbuilder A (VA/SY A) and green circles for shipbuilder B (VA/SY B). The vast majority of the submarine fleet is within 500 mhrs/LT of the mean. The outliers tended to be the first and second of the class. This plot shows the learning curve of each shipyard that built the different submarines.

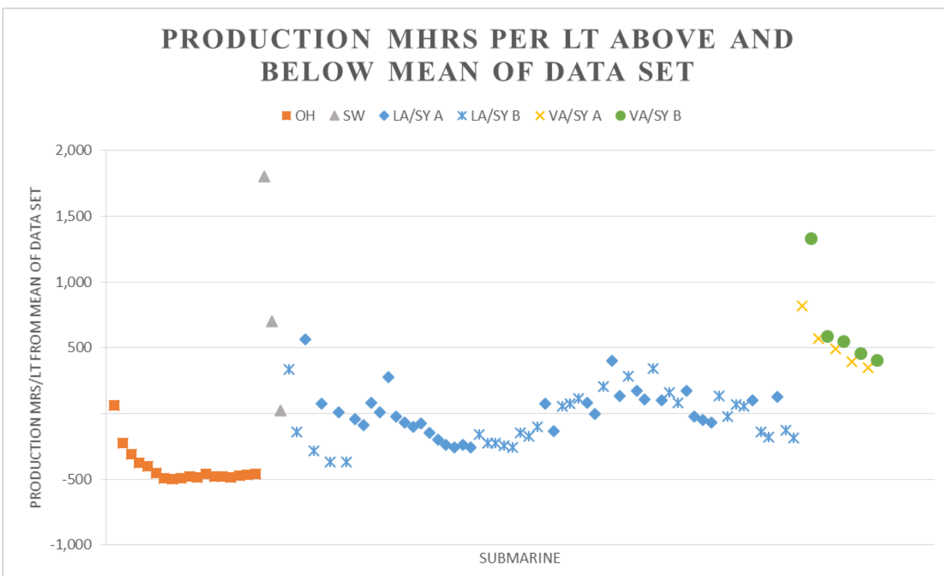

Figure 1. Scatter plot of the difference of production mhrs per LT per submarine above and below the mean production mhrs per LT for all submarines in data set.

The production mhrs were then plotted against the outfitting density for the OPS, Figure 2, and machinery compartments, Figure 3. While no obvious correlation can be

drawn throughout the submarine fleet relating outfitting density to production mhrs, there does appear to be a positive correlation between outfitting density and production mhrs within each submarine class.

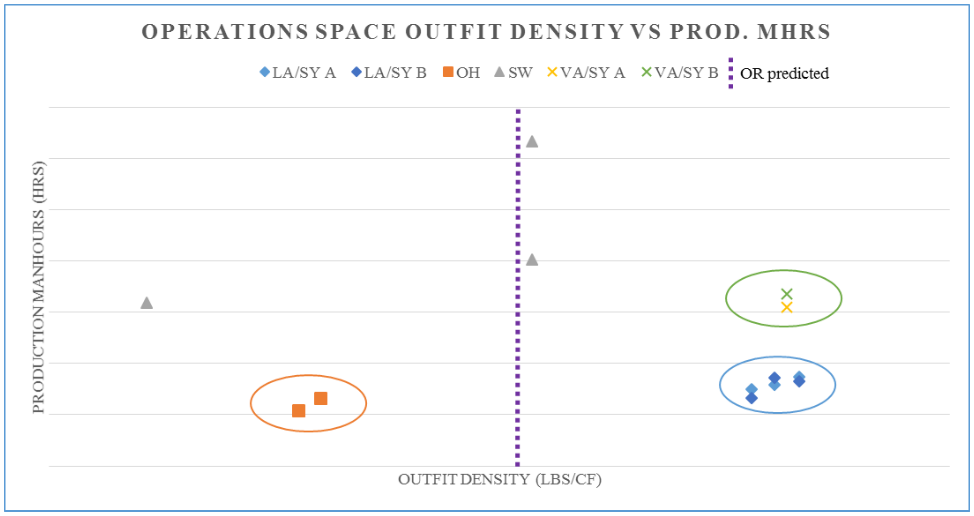

Figure 2. Outfitting density verses production mhrs of the OPS compartment per submarine class by flight

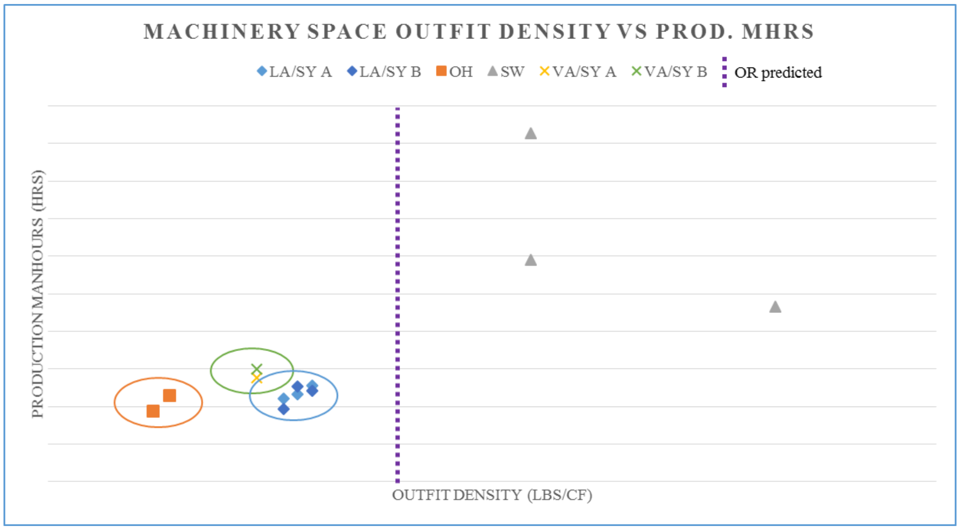

Figure 3. Outfitting density versus production mhrs of the machinery compartment per submarine class by flight

Since the construction method and processes used for the *Virginia* class will be leveraged for the *Ohio Replacement* class, the learning curve for the shipyards contracted

to build the submarines should be minimal and be achieved faster than for the prior classes. For the *Ohio Replacement* program, the expected production mhrs/LT will be within 500 mhrs/LT of the fleet mean production mhrs/LT after the learning curve if the class production follows Figure 1. In Figure 2, the *Ohio Replacement* predicted OPS compartment outfitting density is approximately half way between the *Ohio* class and the *Los Angeles* and the *Virginia* classes. This means the production mhrs for the *Ohio Replacement* OPS compartment should be between what was reported for the *Ohio* class and the *Virginia* class. In Figure 3, one can see that the *Ohio Replacement* predicted machinery compartment outfitting density is greater than the machinery compartment outfitting densities for the *Los Angeles*, *Ohio*, and *Virginia* classes but less than the *Seawolf* class. The prediction is that the production mhrs for the *Ohio Replacement* will be more than the reported production mhrs for the *Los Angeles*, *Ohio*, and *Virginia* classes but less than for the *Seawolf* class.

This analysis attempted to investigate the relationship between outfitting density and construction cost through the use of production mhrs. The assumption was that as more components are installed into a limited volume that it would potentially take more production mhrs to complete. The result was a positive correlation between the outfitting density and production mhrs of the OPS and machinery compartments. More data is needed for the *Virginia* class to be able to validate the correlation.

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I. INTRODUCTION

A. OBJECTIVE OF STUDY

The National Shipbuilding Research Program (NSRP) completed a study in 1992 wherein the NSRP identified the top level parameters that have an effect on the cost of shipbuilding. These parameters are arrangements, simplicity, material, standardization and fabrication requirements (Naval Surface Warfare Center Carderock Division 1992, 7B2-1). This research dives into the arrangement aspect evaluating outfitting density, how tightly the submarine's items are installed within a determined volume, and the possible correlation on the production hours to construct the submarine.

B. PROBLEM STATEMENT

The 2011 Budget Control Act creates a climate where cost reductions dominate the program manager's decision-making process. Consequently, it is important for submarine program managers to understand the limitations of submarine construction cost estimates. Though there are numerous avenues one can explore, a thesis by Benjamin P. Grant in a June 2008, "Density as a Cost Driver in Naval Submarine Design and Procurement," suggests the potential of applying a modular outfitting density factor in the submarine cost estimating process. Modular outfitting density is defined as the degree of compactness of a particular modular area. Using this factor will facilitate understanding the difference between new construction submarines and past classes to identify potential areas of potential growth/reduction. This research examines modular outfitting density relative to the Ohio Replacement Class Submarine Program and how the modular outfitting density affects the construction cost of submarines.

C. IMPLICATIONS

The results of this study will evaluate outfitting density of historical submarines to aid Naval Sea Systems Command (NAVSEA) 05C cost estimators in determining whether or not a density-based cost-estimating relationship (CER) should be developed to

account for any construction cost implications due to the outfitting density of certain compartments of the submarine.

II. BACKGROUND

A. SUBMARINES

The focus on this study is the United States (U.S.) Navy Submarine Force. NAVSEA 05C cost estimators are preparing the costing position for the *Ohio* Replacement and *Virginia* class Payload Module Programs. This study will aid in the submarine baseline cost development and determine whether or not a density-adjusted CER is appropriate. To understand the potential effect outfit density may have on submarine production and the limitations to this study, one needs to understand how submarines are designed and constructed and how the weight and costing estimates are developed.

1. SUBMARINE CONSTRUCTION

Today, submarines are constructed in the U.S. by two major shipyards, General Dynamics Electric Boat (EB) and Huntington Ingalls Newport News Shipbuilding (NNS). EB is located in Groton, Connecticut with a modular construction, manufacturing and outfitting facility in Quonset Point, Rhode Island. NNS is located in Newport News, Virginia. In terms of infrastructure, both shipyards have full capability to produce submarines, and through different types of purchasing agreements and contracts, have historically been involved in building most classes of U.S. Navy submarines.

a. Historical Modular Shipbuilding

Between 1941 and 1945, Henry Kaiser implemented the Kaiser Shipbuilding Techniques, which revolutionized the U.S. shipbuilding industry. His modular construction philosophy enabled 18 shipyards to produce 2,751 *Liberty* ships in support of World War II (Hepinstall 2014). According to Hepinstall (2014, 5), “modular construction is a process where individual modules or volumes are constructed off-site, typically under controlled plant conditions, stand alone, are transported to the site and then assembled together onsite to make up a larger structure.” Kaiser’s modular philosophy developed what is known today as the “1-3-8” rule. This means that every

hour that is used to accomplish a task in a shop environment will lead to a corresponding three hours in a temporary environment and an additional eight hours in the final stages of the construction effort (Seubert 1988). In shipbuilding, this means every hour of production in the shop environment will follow with three hours in assembly and eight hours inside the hull. Previously, submarines were assembled piece by piece on location, typically on the shipbuilding ways or inclined railway. The submarine hull was constructed, and then large holes were cut out of the top to allow equipment to enter the vessel and be installed. There were numerous issues that drove up the man-hours (mhrs) for producing the ship: crowded environment with limited space for mobility, compartments easily filled with smoke, paint and other fumes, everything was on an angle (parallel to the incline of the ways or rail system), poor lighting, and shops, tools, and supplies are not co-located. With emphasis on the 1–3-8 rule, technology and production development, and the need for a safer working environment for production personnel, submarine modular construction evolved.

b. Submarine Modular Construction

Modular shipbuilding methods for submarines were implemented beginning with the *Ohio* class submarines in the early 1970s (Williams 2005). The development of the modular construction technology throughout the *Ohio* class production line enabled the builder to reduce production labor hours from the lead ship significantly. During this time period, the *Los Angeles* class was also in production using the more traditional method of joining empty cylinders then loading individual pieces through the topside hatches (Holmander and Plante 2011). Modular construction technology continued to develop through the *Seawolf* and *Virginia* classes enabling advances toward outfitting the modules, thus reducing production hours needed for assembly as demonstrated in Figure 1. The higher the percentage complete of the module prior to hull assembly, the more the production yards can take advantage of the aforementioned 1–3-8 rule. Outfitting is defined as the action of installing various ship systems and equipment that allow the ship to operate and perform various missions. The scope of outfitting includes structural, piping, electrical power distribution, heating, ventilation and air conditioning (HVAC), joiner and insulation (Hepinstall 2014). Today, the modules being produced for the

Virginia class have approximately 95 percent of the outfitting completed prior to their assembly (Williams 2005).

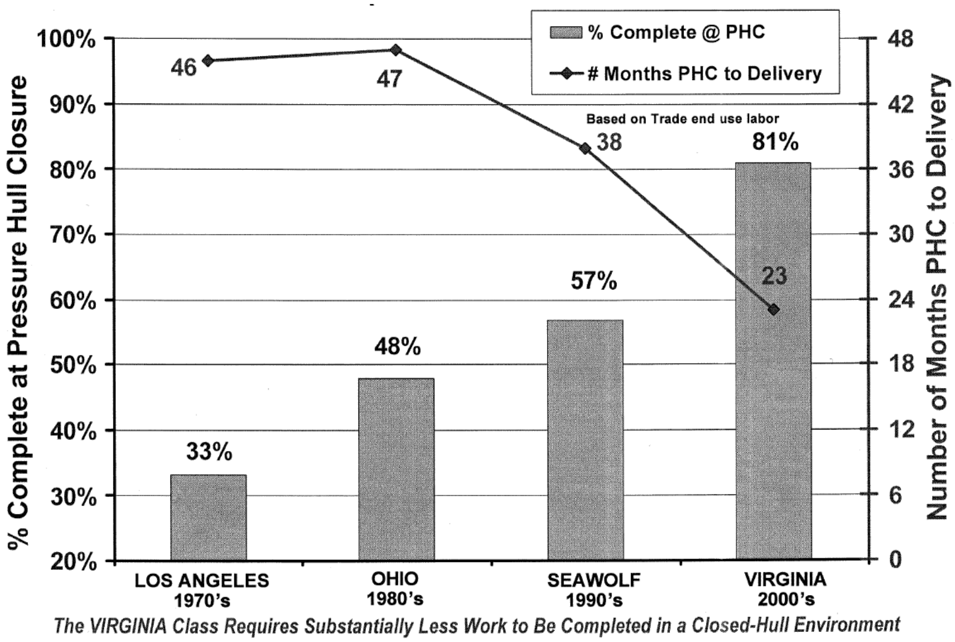

Figure 1. Outfitting completed at pressure hull closure by submarine class at Electric Boat (EB) (from Williams 2005)

The ability to install equipment and advance outfitting during construction is greatly improved using a process known as end loading. A "raft" is an open unit with as much of the outfitting as possible installed that slides into the module, shown in Figure 2. This process takes advantage of the shipbuilder's 1–3-8 rule with the goal of reducing the resultant production mhrs, and it also enables outfitting to take advantage of space that was inaccessible when working inside the module (Holmander and Plante 2011). A drawback of the end loading method is that the submarines are designed with an extra foot of beam. The extra volume is to accommodate the flexible mounting and to slide the raft into the hull cylinder; however, that extra space is not usable for outfitting components or for any other function that could take advantage of the extra volume. Though this is desirable for the construction process, it is undesirable for the submarine community in terms of procurement costs. The Navy is purchasing a larger submarine with volume that is unusable to the submariners.

Figure 2. A “raft” being loaded onto USS *New Hampshire* (SSN 778) at EB’s Quonset Point facility (from Holmander and Plante 2011)

2. Design Philosophy

With each class of submarine design, the design philosophy evolves. The geo-political environment and current economic pressures influence the focus of the classes’ design philosophy.

a. Historical

History is a very important factor in submarine design. Shortly after the Cold War began, with adversarial submarines gaining capability, U.S. submarine designers focused on the anti-submarine warfare (ASW) mission, emphasizing quieting technology and intelligence, surveillance and reconnaissance (ISR) capability (Naval Undersea Warfare Center 2014). The submarine classes of the 1960s included the *George Washington* ballistic missile submarines and the *Permit* class fast attack submarines. As the ballistic missile capability became a key leg in the country’s nuclear triad, emphasis was also focused toward increasing subsurface launched ballistic missile (SLBM) technology.

In the 1970s, ASW, ISR, and SLBM capability were still a top priority. The *Los Angeles* fast attack submarine class was designed to be able to escort and track with an aircraft carrier battle group, thus speed was also an important characteristic (Naval Undersea Warfare Center 2014). *Ohio* class ballistic missile submarines began production increasing the SLBM quantity carried on the submarine. Not only was the *Ohio* class an invaluable leg of the nuclear triad, but they were also the largest submarines the U.S. Navy had designed and built to date. During this time, EB began revamping their submarine production facilities and methodologies to incorporate a more modular methodology to aid in the *Ohio* class construction (Williams 2005).

In response to the U.S. threat, Russia expanded its operating areas into the Arctic Ocean and produced two new classes of threatening submarines: the SSBN *Typhoon* and SSN *Akula* classes. In the 1980s, the *Los Angeles* class design was modernized with technological improvements in combat systems, vertical launch technology for Tomahawk missiles and ice-breaking capability. Designs for the new *Seawolf* class were developed and contracted for 29 submarines (Naval Undersea Warfare Center 2014). The *Seawolf* class had that era's ultimate capability for ASW, ISR and polar missions, and was fast, acoustically superior and could navigate in deeper waters than any other fast attack submarine. All this capability came at a price, however, and with the fall of the Berlin Wall and the close of the Cold War (Naval Undersea Warfare Center 2014), resources to support the submarine community became scarce. This change in global landscape placed less of a priority on the ASW mission, and resulted in the cancellation of the *Seawolf* class after only three submarines were built.

Nonetheless, the submarine community soon came to realize that a new fast attack class was needed to replace the *Los Angeles* class. With the rising threat of terrorism, the fast attack strike mission took precedence (Naval Undersea Warfare Center 2014), and by the late 1990s, the *Virginia* class submarines were designed and contracted to address the emerging needs. The *Virginia* class, as well as four converted *Ohio* class guidance missile submarines (SSGN), addressed the new emphasis on ISR, special operations forces (SOF) mobility and irregular warfare, and strike mission capability. With the anti-access/area-denial (A2/AD) environment of the Chinese and Russians developing and

producing increased capability in their submarines, the ASW mission emphasis re-emerged with a large technological effort being placed on acoustic superiority within the budgeted cost constraints in place from the Budget Control Act of 2011.

b. Design/Build to Design/Build/Sustain

In the late 1980s and early 1990s, a paradigm shift occurred within the submarine design community. With the cancellation of the tumultuous *Seawolf* class production, there was tremendous pressures to reduce costs for the *Virginia* class and to ensure the community did not repeat the issues that brought the *Seawolf* class to a close. The goal was to reduce production labor by 40 percent from the USS *Seawolf* (Williams 2005), so the submarine community shifted the design focus to take the construction process into account. The design community harnessed the knowledge of the current workforce that had experience from the *Los Angeles, Ohio,* and *Seawolf* classes. As design efforts focused on designing for production, many sustainment issues needed to be addressed, such as the following:

> While outfitting modules are heavily pursued as a cost-cutting measure in new construction, they can have a tendency to cause accessibility issues for maintenance. …outfitting modules should be vetted through Design-for-Maintenance lens during the design process to ensure total ownership cost goals are achieved. (Hepinstall 2014, 10)

The Design/Build/Sustain philosophy alters the design focus to be on production as well as on sustainability. The use of rafts in submarine construction means that the equipment on the raft can be installed in many locations that production personnel were formerly unable to access using more traditional means of construction. The sustainability issue is that once the raft is slid into place and the pressure hull welded together, some of the equipment that was installed on the raft becomes inaccessible. Sustainability mhrs increased as a result of having to remove interferences, work the item, and then reinstall the interferences. This created unintended rework, and thus increased sustainability costs. Accounting for the sustainability factor in the design, mitigates these types of issues.

3. Submarine Volumetrics

For a submarine to be able to submerge, the density of the entire envelope of the submarine must be equal to the density of the water in which it intends to submerge. This constrains the characteristics of the submarine. While computing the ideal size of the submarine, thorough analysis is performed in determining the diameter of the hull and the optimal length-to-diameter ratios for hydrodynamic characteristics. On a ballistic missile submarine the missile tubes may be the determining factor for the diameter of the hull. Other diameter drivers are the propulsion plant, weapons storage, and internal volume requirements for tanks and other system elements. Limitations for diameter include draft restrictions for dry docks and ports, and any displacement limitations that may have been imposed on the design. For all submarines, if the diameter is too large, the deck heights will be too high making efficient utilization of the space difficult. If the diameter is too small, the deck height will be too short, resulting in insufficient headroom for the crew (Jackson 1992, 419). There are numerous studies that have analyzed the optimal diameter as a function of deck spacing. One of those states that

> the optimum has not been reached by any major submarine since the HOLLAND type at the beginning of this century. As more and more equipment is required in present submarines, it is unlikely that this optimum will ever be obtained due to the limitations on draft in most of the harbors of the world. (Jackson 1992, 419)

Modern-day modular construction methods have added to this complexity. Additional space must be built into the diameter to accommodate flexible mounting and other support structure for housing the raft units. Unfortunately, this additional space is unusable for outfitting systems. Once the diameter is set, the length is determined. There are optimal length-to-beam ratios that can be used to initially determine the length of the submarine.

Once these characteristics are set, there are two limitations that typically occur as the program progresses through the design process. If the available volume of the submarine is arranged to its extent and the submarine has not reached the displacement needed to submerge, then the design is considered "volume limited." To reach the necessary displacement, lead ballast is added into the design to consume the difference.

On the other hand, if the weight reaches the displacement needed to submerge prior to arranging all the necessary systems on board, and then the design is considered “weight limited” and weight saving measures are required. Options would be to add length to the parallel mid-body, or to evaluate ways to reduce weight. While the length and diameter could feasibly change if a program warranted lengthening the boat, this type of change is very costly and has many political implications. The vast majority of past submarine designs have been volume limited rather than weight limited.

4. Weight Estimating

Estimating the weight of a submarine is a complex iterative process that occurs through each phase of the acquisition process. Some factors that make submarine weight estimating unique are that submarine volumetrics and Archimedes principles must be considered in parallel with the weight estimating. “The fundamental goal in submarine design: during its entire life, the submarine shall be capable of achieving neutral buoyancy and zero trim for all design conditions” (Society of Allied Weight Engineers, Inc. 2007).

In concept development, preliminary light ship weight estimates are formulated from curves, formulas, or experience. The analysis of alternatives (AoA) designs are analyzed using analogous and parametric estimates. The chosen concept’s weight estimate will serve as the baseline for the preliminary design phase. Any major requirement or characteristic changes will update the baseline to a new baseline. This initial baseline will serve as the Milestone A position.

During preliminary design, the design is refined. Since submarine designs are typically evolutionary based on past submarine designs, the weight is derived from refined analogous estimates based on historical data and parametric estimates. Some of the weight data may be calculated based on some completed modeling, completed system descriptions, or arrangement approvals. Before entering detail design, an Accepted Weight Report (AWE) will be accepted by NAVSEA. The AWE is the best representation of the submarine’s weight and hydrostatic characteristics at Milestone B.

In detailed design and construction phases, the weight estimates for the submarine are more defined as the program progresses through detail design. As models are completed and drawings approved, the weight estimate should incorporate more details and evolve to a majority of calculated weights. Then during the construction process, the actual weights for key items may be included in the weight estimate based on procurements. Post construction, the construction yard will complete an inclining experiment—a stability test that will validate the condition A weight and centers of the submarine, and a trim dive—a neutral buoyancy test that validates the weight and locations of the permanent ballast (Society of Allied Weight Engineers, Inc. 2007). From these tests, the Final Weight Report (FWR) for the delivered vessel is generated. The unwritten goal is for the delivered submarine to be within one half of a percent of the expected weight.

a. Weight Classification Systems

Weight information for a particular hull will be classified by an organizational structure. "The weight classification system provides guidance and definition at the system and subsystem level and aids in preparation of a complete and accurate estimate" (Society of Allied Weight Engineers, Inc. 2007, 63). Modern hulls use the Expanded Ship Work Breakdown Structure (ESWBS). Prior classes have used the Ship Work Breakdown Structure (SWBS) and Bureau of Ship Consolidated Index (BSCI). Since prior submarine weight breakdowns were classified under different systems, extra care must be taken when comparing historical data. Manipulation of the data may be necessary to account for the differences among the various breakdown structures to ensure an appropriate comparison. Table 1 displays the first level of the ESWBS breakdown. Group 100 accounts for all the structural elements, hull structure, decks, bulkheads and equipment foundations. Group 200 encompasses the propulsion plant, both nuclear and non-nuclear components, from the reactor to the propeller or propulsor. All the power generation components and cabling are contained within group 300. Group 400 represents all the combat systems, communications, and navigation systems. Group 500 includes the auxiliary systems such as steering, anchor handling, and HVAC. Outfitting and furnishings, such as offices, medical, stores, berthing, joiner work and paint are allocated

to group 600. Group 700 is armament, including guns, torpedo launchers, strategic weapon systems components, torpedo equipment and depth charges. Variable loads are included in group 800. These variable loads encompass liquid volumes in tanks, expendables, food, and consumable stores. This breakdown also serves as the backbone of the construction cost baseline.

Table 1. ESWBS description (after Society of Allied Weight Engineers, Inc. 2007)

Group #	ESWBS Name	Description, examples
100	Hull Structure	Shell plating, decks, bulkheads, framing, superstructure, pressure hull, foundations
200	Propulsion Plant	Reactor, turbines, gears, shafting, propeller/propulsor, steam piping, shielding
300	Electric Plant	Ship service power generation, cabling, lighting, emergency electrical
400	Command and Surveillance	Navigation, communication, fire control, radars, sonars, radios, C2 systems
500	Auxiliary Systems	HVAC, anchor handling, fire control, steering
600	Outfit and Furnishings	Hull fittings, paint, insulation, berthing, offices, storerooms, medical
700	Armament	Guns, missile launchers, ammo, torpedo equipment, depth charges,
800	Variable Loads	Tank liquid loads, expendables, consumables

b. Displacement

Displacement is defined as the weight of the volume of water that is displaced by the submarine. Since the submarine operates both on the surface as well as sub-surface, there are multiple displacements for each submarine that correlate with that submarine’s conditions. The displacement of a submarine that is submerged and is operating at some

depth is referred to as the Condition N Submerged displacement. The loading conditions of the variable loads for the submarine in Condition N are defined in *Naval Ships Technical Manual* (NSTM) Chapter 096 and serve as the "typical" submarine load out for a typical mission over a typical length of time. To submerge the submarine from a surfaced condition, the boat opens its MBT vents and floods the MBTs with the surrounding water. The difference in displacement of a submerged submarine and a surfaced submarine, in Condition N, is equal to the amount of main ballast tank (MBT) water. The surfaced condition is referred to as Condition N Surfaced. The Condition A displacement, also known as the Light Ship (LS) weight, is determined by removing the variable loads and variable ballast water from the Condition N Surfaced displacement. The Dry Weight of the submarine includes all the Group 100 – 700 weights. Adding the nuclear and non-nuclear operating liquids to their respective systems, increases the displacement of the submarine to her Condition A-1 displacement. Permanent lead ballast lines the interior of the MBTs and other key locations within the pressure hull. This lead enables the submarine to submerge with the given MBT volume, and also enables the submarine to have growth margin for future modernizations. The amount of this lead defines the difference between the submarine's Condition A-1 and Condition A displacements. Condition A displacement is also referred to as the submarine's light ship weight. Figure 3 summarizes the difference among the submarine displacement classifications.

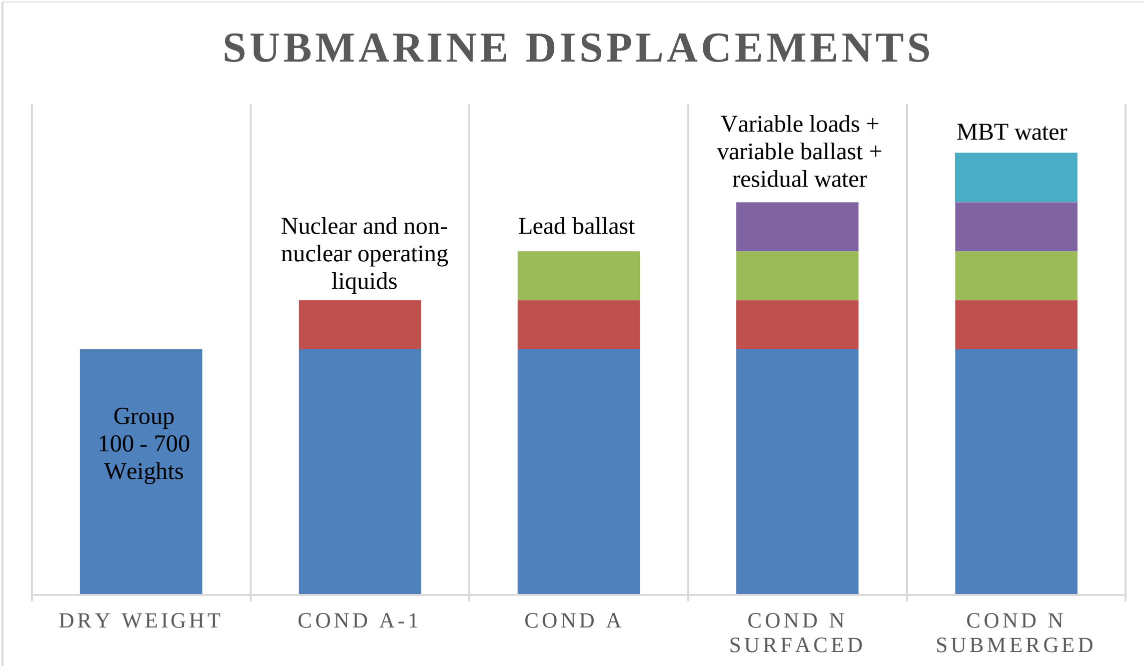

Figure 3. Submarine displacements (after Society of Allied Weight Engineers, Inc. 2007)

c. *Key Deliverables*

The weights of the design are tracked via a quarterly weight report throughout the preliminary design, detail design and construction phases. The Accepted Weight Estimate (AWE) is the weight report that is the best representation of the submarine at Milestone B and relays details of the design at the three-digit ESWBS level, along with the corresponding loading condition, and hydrostatic characteristics. This AWE contractually obligates weight growth margin, the ability to grow in weight, to the different stakeholders: NAVSEA, Naval Reactors, and design yard and build yard. There is a percentage of the A-1 Weight that is required by the ship specifications to be available when the ship delivers. This is for future growth and is allocated for the service-life of the submarine. The AWE serves as the baseline weight for the Milestone B costing position for projected construction costs.

The Final Weight Report (FWR) reflects the final status of the delivered ship design and construction effort. The weights used in this analysis are derived from the FWRs.

d. Limitations

At the AWE, a large percentage of the weight is estimated though analogous methods or projected nominal weights from suppliers. Many of the component and tank volume estimates have many assumptions, and are dependent on communications among the government, design yard and suppliers. There is high risk that the light ship weight will grow through the detailed design process, especially as arrangements are approved and drawings begin to be developed. The weights that are calculated from the 3-D product model are dependent on the modelers' assumptions and the consistency of modeling practices between them. From a weight perspective, this risk is mitigated through the use of weight growth margin. However, since this weight estimate is used for the construction cost estimate, this growth risk is not directly accounted for in the cost estimating process.

B. COST ESTIMATING

1. Acquisition Cycle

Growth in U.S. Navy shipbuilding costs have historically exceeded the rate of inflation. The Navy's budget for procurement is unable to support the continued growth in ship acquisition costs. Recent regulation, like the Budget Control Act of 2011, has put an additional strain on the Navy's budget. "The economy-driven factors (material, labor and equipment) account for roughly half the overall rate of increase, whereas the customer-driven factors (complexity, standards and requirements and production rate) account for the other half" (Arena et al. 2006). There is tremendous pressure on the shipbuilding community to reduce the cost of submarines and to demonstrate that cost targets developed by Congress can be achieved.

The cost estimating process is very similar to the weight estimating process as a program progresses through the acquisition cycle. Many of the estimation methods are similar in philosophy. Early in the concept refinement phase, cost estimates are analogous ratios based on the concept being considered and how similar or dissimilar they are to historical data. Historical cost data needs to be normalized for content, historical prices, and inflation escalation. As a concept is selected and refined, parametric estimates for the

Milestone A cost position can be developed based on mathematical relationships between cost, and various independent variables. Cost estimating relationships (CER) are developed to estimate the cost of new systems where analogous relationships are not applicable. Throughout preliminary (Technology Development phase) and detail design (System Development and Demonstration phase), the cost estimating is refined iteratively using an engineering build-up technique to develop parts of the construction costs. As bills of material are produced, using shipyard standards, the cost estimators can refine their estimates appropriately. Then, as actual purchasing agreements are made with suppliers, actual costs can be incorporated into the estimate. The NAVSEA 05C Cost Estimating Handbook examines each of the cost estimating methods throughout the acquisition process. Figure 4 is a summary of the cost estimating methods used throughout the acquisition process.

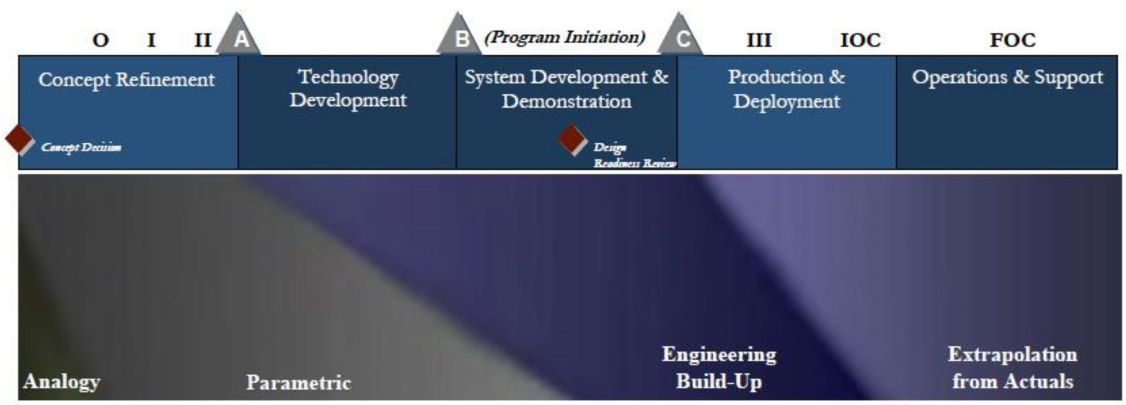

Figure 4. Common estimating methods by life cycle phase (from Deegan 2004)

2. Construction Cost Estimating

Basic Construction Costs (BCC) are reported in the Procurement Budget Exhibit 5 (P-5). There are seven main categories of the P-5: basic construction, construction plans, change orders, government furnished materials (GFM), ordnance, escalation and other costs (Deegan 2004). The BCC is the shipbuilder’s portion of the ship’s end cost. This includes shipbuilder direct labor, indirect labor, material costs and profit associated

with building a ship. There are multiple methods that the cost estimators use to develop the BCC estimates (Deegan 2004).

a. Weight Based Cost Estimating

For many current estimating methods, weight is used as the key parameter to determine costs. "Weight is the most consistent physical property that the designer is able to provide to the ship cost estimator. Therefore, the most common parametric form employed in ship cost estimating uses weight as the technical parameter" (Deegan 2004). The cost estimator will use the estimating methods described above with the predictive weight information for the vessel to be construction to develop the CERs and the BCC.

b. Other Cost-estimating Methods

Other estimating methods include Product-Orientated Design and Construction (PODAC) cost modeling and the bottom's-up method. The PODAC cost model is product-based and process-driven, as opposed to system-based and weight-driven. It is sensitive to shipyard processes and techniques. For example, the PODAC cost model develops the labor CER as a function of shipyard processes versus an hour per ton relationship based on reported cost data and ship weight reports. The bottom's-up method requires a granular fidelity in the ship design to be able to estimate accurately. This method identifies each item, material and labor, in the schedule, and builds the estimate up. Due to the complexity of the design, this process is very elaborate.

c. Limitations

The cost estimating team has to make many assumptions to develop the cost estimate. These assumptions may not hold true throughout the development process. For example, data that is based on historical data is at the mercy of the fidelity of the reported data. Also, cost estimates that are based on weight estimates carry a large uncertainly due to having two factors of estimation in the process (both cost and weight). Political pressures may also add biases into the estimating process, putting pressure on the program to limit the size of the ship in efforts to control the cost but could compromise mission. The 1992 RAND study concluded that

> the most extreme result of assuming that cost is a direct function of weight has been the imposition of displacement limitations on some ship types during the design process in the misguided expectation that such a limitation would control costs. (Naval Surface Warfare Center Carderock Division 1992, 7B2-1)

C. SUMMARY OF PREVIOUS RESEARCH

1. Key Findings from Prior Thesis Research

Research in evaluating ship construction costs to understand the cost drivers has been studied in the past and continues to be studied. Three theses conducted at Naval Postgraduate School and Massachusetts Institute of Technology have evaluated the cost drivers from different perspectives.

a. NPS Thesis by LT Benjamin Grant

In 2008, Lieutenant (LT) Benjamin Grant wrote a thesis for the Naval Postgraduate School (NPS), "Density as a Cost Driver in Naval Submarine Design and Procurement." The purpose of this study was to investigate the relationship between submarine density and costs and to determine if a relationship exists and what could be learned for the design and procurement of U.S. Submarines. Grant's key findings were (1) cost and performance risk are asymmetric, meaning that programmatic risk associated with underestimating the volume required for the submarine is greater than the programmatic risk associated with producing a submarine that is unnecessarily large; (2) weight reduction efforts increase costs; (3) density and cost exhibit a family of "U"-shaped curves; and (4) density management alone will not reduce costs.

This thesis will examine Grant's preliminary work and refine it to investigate the relationship between outfitting density by compartment and production costs.

b. MIT Thesis by LT Ungtae Lee

In 2014, LT Ungtae Lee explored and improved the current weight based parametric method in early cost estimation using mainly outfitting density and power density in the naval surface fleet. The key findings of LT Lee's study were that he developed a CER using electrical power density and light ship weight, and demonstrated

the relationship between outfitting density and electrical power density versus cost per ton for naval surface vessels.

c. MIT Thesis by LT Aaron Dobson

In 2014, LT Aaron Dobson quantified, assessed, and analyzed cost versus subsystem complexity in an effort to refine the current cost estimating relationships used in U.S. Navy shipbuilding. The result of his study was that acquisition contract cost per unit was highly correlated with unit complexity.

D. SUMMARY

With this past research as a starting point, the thesis research herein attempts to examine past submarine classes to determine if a correlation exists between the outfitting density of similar compartments and costs.

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III. METHODOLOGY

A. GENERAL APPROACH

1. Submarines Selected

Initially the submarines selected for this study dated back as far as the weight data is available. The intent was to see if correlations could be drawn between many submarine classes. Depending on the submarine class, the shipbuilders ranged from EB and NNS to Mare Island Shipyard, Portsmouth Shipyard and Charleston Naval Shipyard (Federation of American Scientists 2015). The mathematical model that quantifies the efficiencies gains from repeatable actions, known as the learning curve, has an important role in shipbuilding. Each shipbuilder has its own learning curve. Since EB and NNS are the only shipbuilders that currently build U.S. Navy submarines, the submarine classes used in the analysis were built by either EB or NNS in order to accommodate each shipyard’s learning curve.

SUBSAFE is a quality assurance program that provides maximum reasonable assurance that submarine hulls will have watertight integrity and recoverability from unanticipated flooding. Though this program is vital to the submarine community, the requirements imposed on design practices, personnel training, material quality, manufacturing processes, and certification are very costly in both material, labor and overhead dollars. The *Los Angeles* class was the first class of U.S. Navy submarine to be entirely designed and built to SUBSAFE requirements, from concept design through the life cycle.

With SUBSAFE requirements and shipyard learning curves taken into account, this analysis will focus on the following submarine classes: *Los Angeles*, *Ohio*, *Seawolf* and *Virginia*. The difference between the pre-*Los Angeles* class submarines and post-*Los Angeles* class submarines are very significant in that the data became too skewed to develop any correlations.

a. Data

Condition A, light ship weight, displacement data was compiled using the vessels' applicable FWR data. This weight includes Group 100 through Group 700 weight data plus the amount of solid ballast. It is appropriate to use the Condition A displacement data since this is representative of the hull and all the components that are installed to create the submarine. The weights for each submarine were divided into the appropriate ESWBS group at the one digit level (e.g., 100, 200... 700). The 200–700 weight groups were added together to represent the outfitting weight when calculating the outfitting density. The 100 weight group identifies the structural components and is not considered outfitting.

End cost and man-hour data were retrieved from the NAVSEA 05C Information Management System (IMS) database. The end cost data for each submarine was escalated to fiscal year (FY) 2015 constant year (CY) dollars and sorted by delivery shipyard. Production mhrs for each submarine was also sorted by delivery shipyard. In conversations with NAVSEA 05C, if outfit density was to be investigated, one would expect the shipyard's production mhrs would increase or decrease based on how tightly the components had to be installed into a limited area. The production mhrs do not encompass engineering and overhead mhrs that are also essential in producing a submarine.

Volume data was obtained using the Booklet of General Plans for the applicable submarine. For this study, molded volume was used except for the *Virginia* Class submarines. The molded volume represents the volume inside the submarine with the inner face of the shell plating as the vessel's interior boundary. Classes prior to *Virginia* loaded compartments right up to the shell framing. Due to the modular construction end loading technique used on *Virginia* class, extra volume is necessary to support the mounts for the rafted units that slide in. For the *Virginia* class, the molded volume was reduced to represent the usable volume of the submarine.

b. Manipulations

The data had to be manipulated to create a consistent analysis. Each class of submarine was an evolutionary design, both in terms of design and organizational structure.

The ESWBS categorization did not exist on all past classes of submarines. The older classes, such as *Los Angeles* and *Ohio* classes, used BSCI. The group weight data had to be evaluated and sorted in order to ensure that weights for the different groups where represented similar data. In addition, over time, there have been some impactful technological improvements external to the pressure hull that needed to be accounted for in the group weight data. Examples include propeller and propulsors, as well as the hull treatments.

The volume breakdown of the analysis needed to be aligned among submarines. The forward operating compartment (OPS), and aft machinery space was proportionally evaluated. For the fast attack (SSN) submarines, the division between the OPS and Machinery compartments was taken at the normal fuel oil (NFO) tank bulkhead, shown in 0 For the *Ohio* class, shown in Figure 6, the missile compartment (MC) is between the OPS and machinery compartments. The outfitting weight data for each submarine was manipulated by longitudinal location to be attributed to the OPS or machinery compartment.

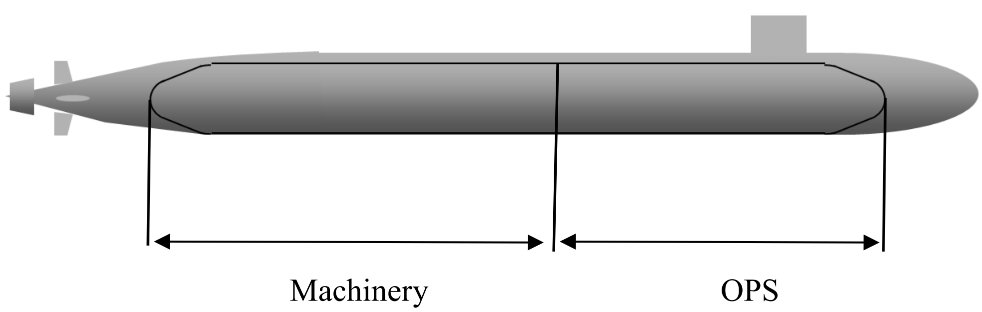

Figure 5. SSN compartment division (not to scale) (after Daley et al. 2014)

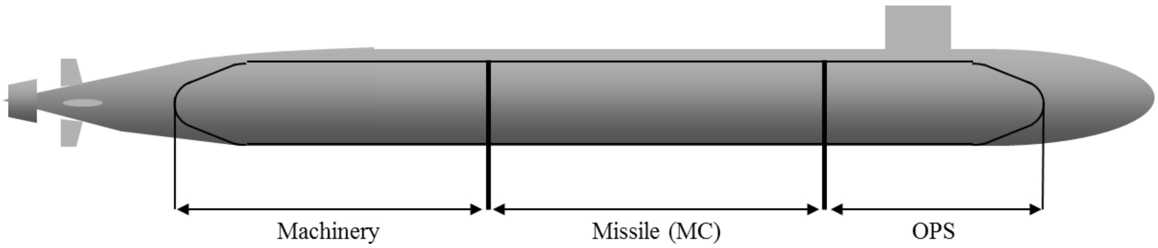

Figure 6. SSBN compartment division (not to scale) (after Daley et al. 2014)

For the submarines in this analysis, the build yard was either NNS or EB. Production data was segregated by each shipyard. By separating the production data for each shipyard, the learning curve aspect of the data is kept separate since each shipyard learns at an individual rate. Starting with *Virginia* class, a unique partnership was made between the two shipyards and enforced by congress with the FY96 National Defense Authorization Act (Schank et al. 2011). For this, data for the *Virginia* class production data has been segregated by final assembly yard.

Lastly, to respect the sensitivity of the production data, all the charts where normalized to mask the sensitive data. NAVSEA 05C is the point of contact if this data needs to be obtained.

c. Limitations

There are many assumptions made for the data used. The data pulled from the IMS was reported by the shipyard and entered into the database. The assumption is that the data was reported correctly and that the person entering that data into the database did so correctly. Another assumption is that the process for recording and reporting the data has been consistent over the past 50 years.

B. DENSITY DEVELOPMENT

Outfitting density was plotted against production mhrs to determine if a correlation exists. Sets of plots were segregated by compartment across the variety of submarine classes to understand if a correlation exists between the type of compartment and the time is takes for the shipyard to produce it. The group 200–700 weight data was interrogated to the three digit ESWBS level and segregated by longitudinal location of

the items on the boat. This developed a weight per compartment result, which then was divided by the useable volume to get the outfitting density of the compartment.

$$Outfitting\ Density\ \left(\frac{lbs}{CF}\right) = \frac{\sum_{200}^{700} W_{compartment}\ x\ 2240}{V_{compartment}} \tag{3.1}$$

where,

$W_{compartment}$ = weight in long tons (LT) of the compartment

$V_{compartment}$ = volume of the compartment in cubic feet (CF)

With the outfitting densities by compartment being determined, the mean outfitting density of each compartment was calculated: OPS outfitting density mean and machinery outfitting density mean. The MC was not evaluated since there was not enough history (one class of submarine) with which to draw a correlation.

Table 2 shows the resulting outfitting density of the individual compartments for each of the submarine classes and is discussed in section III.C.1. The numbers shown in the table are the difference between the class mean and the overall compartment mean. A negative number means that the outfitting density of the compartment for that class is the less than the overall mean for that compartment, or that the components in the compartment are not as tightly installed as in the average compartment. A positive number means that the outfitting density of the compartment for that class is more than the overall mean for that compartment, or that the components in the compartment are installed tighter together that the average compartment.

Table 2. Outfitting density (lbs/CF) by submarine class and compartment (above mean of data set).

	Sub Class	*Ohio* (C4)	*Ohio* (D5)	*Los Angeles*	*Los Angeles* (VLS)	*Los Angeles* (Improved)	*Seawolf*	*Seawolf* (long hull)	*Virginia* (blk I/II)	*OR* (proj)
Outfitting Density (lbs/CF)	OPS	-3.05	-3.34	2.70	3.01	3.34	-0.22	-5.36	3.18	-0.19
	Machinery	-7.82	-8.49	-3.32	-2.76	-2.19	6.43	16.08	-4.39	0.433

For the analysis, plots and resulting regressions were developed for outfitting density versus productions mhrs.

C. ANALYSIS

1. Production Man-hours Analysis

A plot was generated to determine the production mhrs needed to produce each submarine by shipyard. The mean production mhrs for the fleet was calculated, and then the difference between each reported submarine total and the mean was plotted in Figure 7. In Figure 7, colored shapes represent each submarine class categorized by shipbuilder. The orange squares represent the *Ohio* class submarines (OH). The gray triangles represent the *Seawolf* class submarines (SW). *Los Angeles* class submarines are represented by blue shapes with shipbuilder A represented with diamonds (LA/SY A), and shipbuilder B represented with stars (LA/SY B). The *Virginia* class submarines are represented by yellow 'X' for shipbuilder A (VA/SY A) and green circles for shipbuilder B (VA/SY B). The vast majority of the reported mhrs were within 500 production mhrs of the mean. The few outliers can be attributed to the learning curve. *Seawolf* spent well above the average production hours in construction for her lead ship and second of class. *Virginia'*s first and second of class for each shipyard are also high above the mean production mhrs and is on a steady decline toward the mean. Lastly, the first *Los Angeles* class built at Shipyard A was more than 500 mhrs above the mean production mhrs. These outliers are all first and second of class submarines and thus can be attributed to the learning curve for each shipyard on each submarine class. The *Ohio* class mhrs were below the mean of the data set. The slope of the resulting data set was asymptotic to approximately the -500 production mhrs/LT difference from the mean line, representing the shipbuilder maximum learning for the process used to produce the *Ohio* class submarines.

There is a limitation with the *Virginia* class production mhrs/LT data. The Virginia class contract is shared between NNS and EB. Each shipyard builds a portion of the submarine. Each shipyard then assembles one submarine each, delivering a total of two submarines to the fleet per year. The learning curve for each of the submarines has a

mix between each shipyard's production of the set portions and the experience of the assembly for the total submarine. The delta seen in Figure 7 for the *Virginia* class data sets highlights the difference in the learning for the assembly of the submarine.

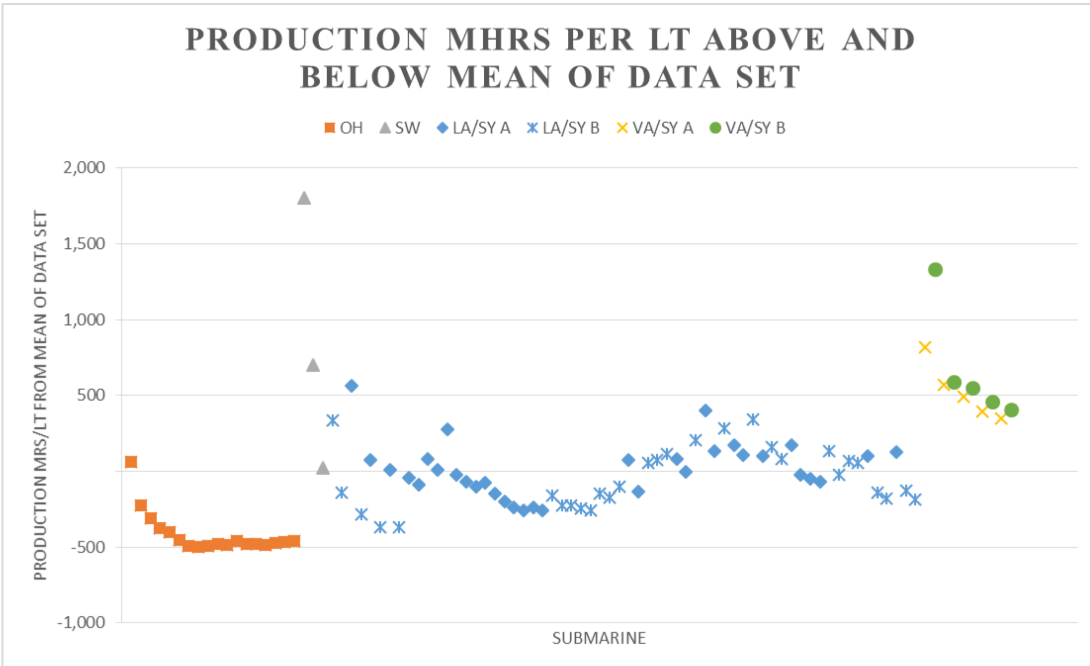

Figure 7. Scatter Plot of the difference of production mhrs per LT per submarine above and below the mean production mhrs per LT for all submarines in data set.

2. Outfitting Density

The resulting outfitting density (difference from the compartment mean) for submarine classes by flight and compartment are shown in Table 2. The *Ohio* class OPS compartment outfitting density was significantly less than for the other classes in the study. The *Ohio* class compartments have more volume available for component installation due to the larger beam. The *Seawolf* long hull was also significantly less than the mean due to the added length of the hull. This is due to the addition of parallel midbody that was added to the production of this vessel. The *Los Angeles* improved class has the greatest density in the OPS compartment, followed closely by the *Virginia* class. Both *Los Angeles* and *Virginia* have the smallest useable diameters of the submarine

fleet. For the machinery compartment, *Seawolf* was the densest and *Ohio* was the least dense. The *Seawolf's* machinery compartment 200, 300, and 500 group weights were higher than the other fast attack submarines. Currently, the prediction for *Ohio Replacement* are 0.19 less than the mean of OPS outfitting density and 0.433 greater than the mean for the machinery compartment density.

3. Correlations

To investigate correlations between the production mhrs and the outfitting density, the data sets were analyzed based on compartments.

The OPS compartment mean outfitting density was plotted against mean production mhrs for the specific class for the OPS compartment in Figure 8. Each flight of each class from each shipyard was grouped close to each other, except for *Seawolf*. There is no correlation across the submarine classes. *Los Angeles* and *Virginia* class have similar outfitting density for the OPS compartment; however, *Virginia* class mean production mhrs are significantly higher, on the order of 50 percent more mhrs. This potentially represents the learning curve needed for the fly-by-wire and other non-propulsion combat system improvements that are unique to the *Virginia* platform. The outfitting density increases on the *Los Angeles* class as the capability increases. As a result, the production mhrs did increase slightly. A similar trend can be seen between the *Ohio* submarine designed for the Trident missiles and the *Ohio* submarines designed for Trident II missiles. There is not enough end data reported for *Virginia* class to witness any correlation within the class. Figure 9 develops some trend lines within the *Los Angeles* and *Ohio* classes. On *Los Angeles* class, for every unit increase in density in the OPS compartment, approximately 222,382 additional mhrs will be needed with a linear reliability of 0.65. For the *Ohio* class, for every unit increase in density in the OPS compartment, 403,703 additional mhrs will be needed with a linear reliability of 1.0. There are only two data points for the *Ohio* class, so the linear reliability value is 1.0.

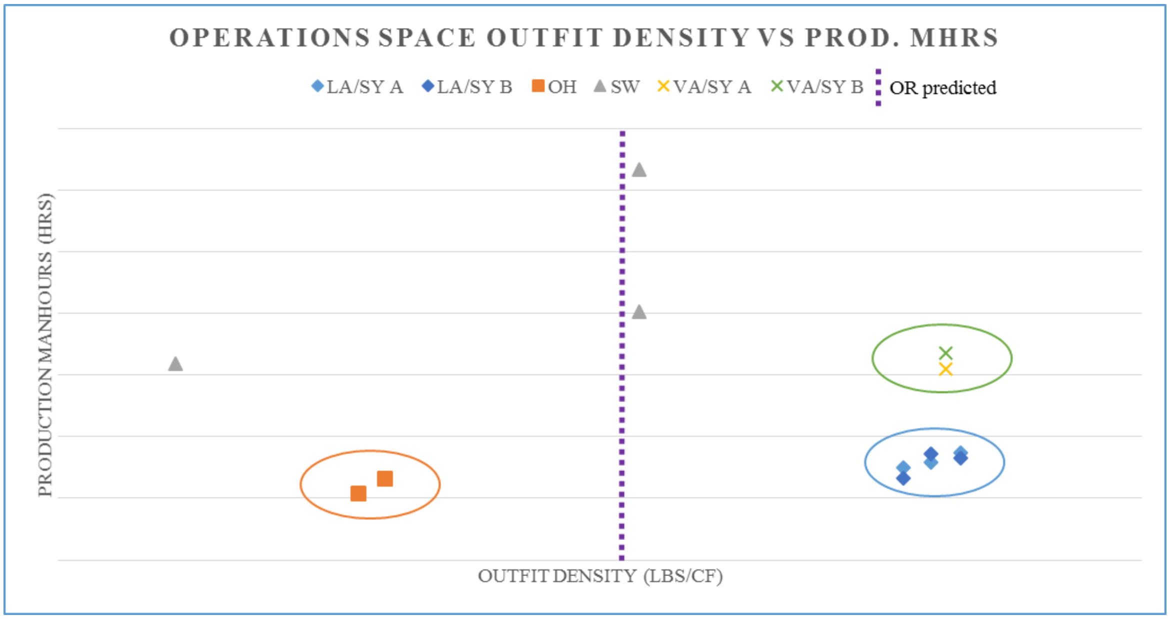

Figure 8. Outfitting density verse production mhrs of the OPS compartment per submarine class by flight

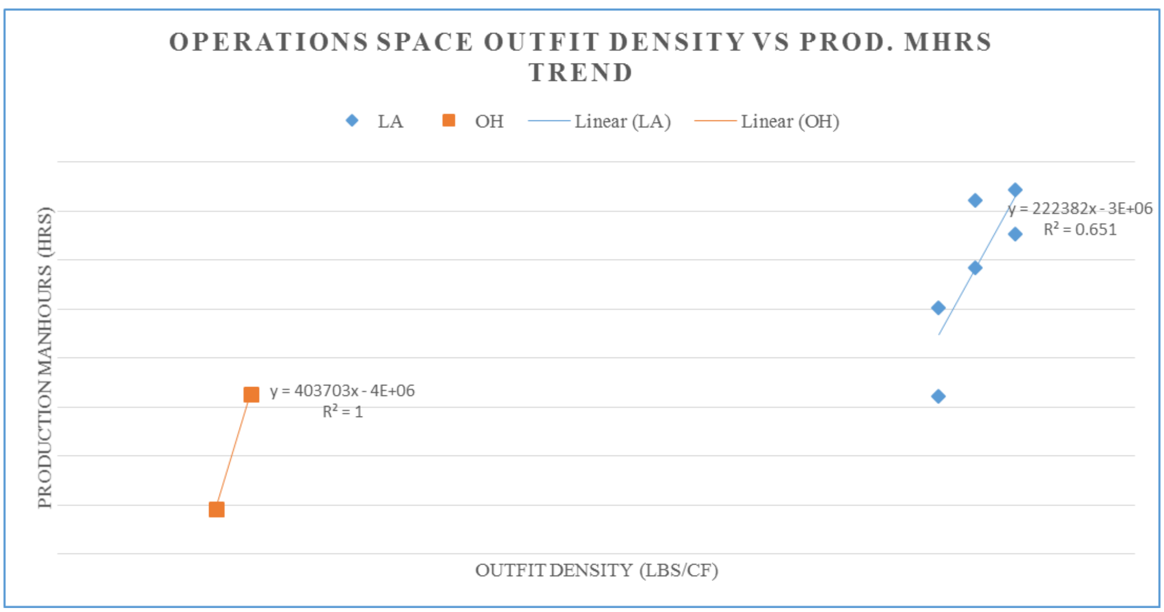

Figure 9. Outfitting density verse production mhrs of the OPS compartment trend analysis for LA class and OH Class.

The machinery compartment mean outfitting density was plotted against mean production mhrs by submarine class for the machinery compartment in Figure 10. The outfitting densities for *Los Angeles, Virginia* and *Ohio* class submarines are very similar, thus it was expected that the production mhrs were very close, within 25 percent of one another. Within each of the submarine classes, there was a slight production mhrs increase as the outfitting density increases. These trends are shown in Figure 11. There was not enough end data reported for *Virginia* class to witness any correlation within the class. On *Los Angeles* class, for every unit increase in outfitting density in the machinery compartment, approximately 371,201 additional mhrs will be needed with a linear reliability of 0.66. For the *Ohio* class, for every unit increase in outfitting density in the machinery compartment, 605,179 additional mhrs will be needed with a linear reliability of 1.0. There are only two data points for the *Ohio* class, so the linear reliability value is 1.0.

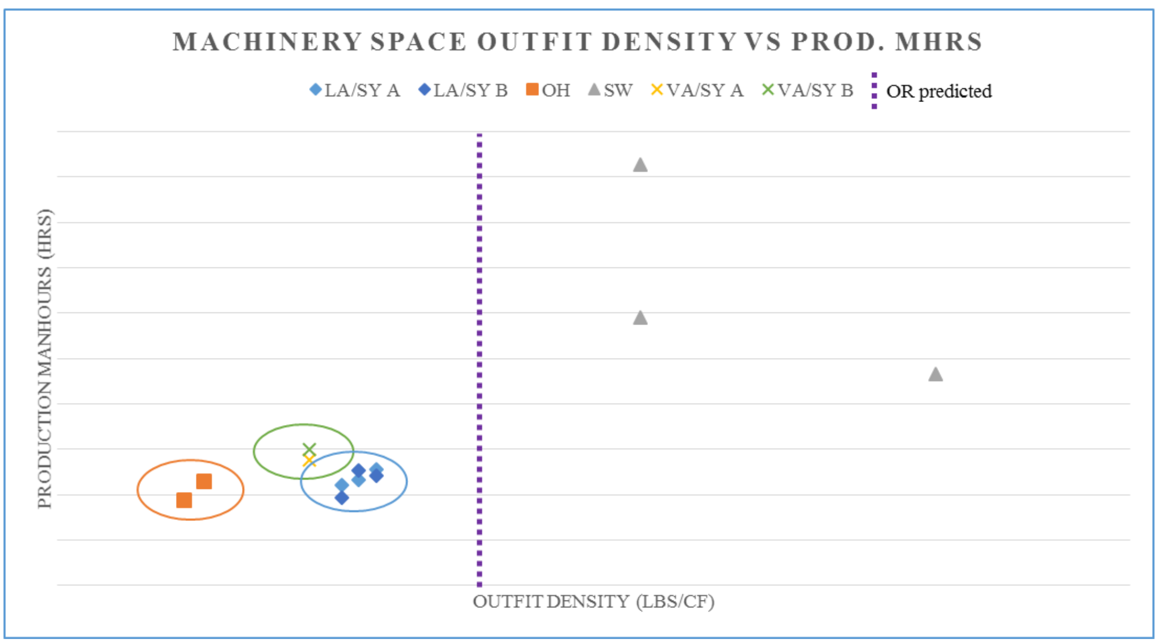

Figure 10. Outfitting density of the machinery space per submarine class by flight versus mean production mhrs per submarine class by flight

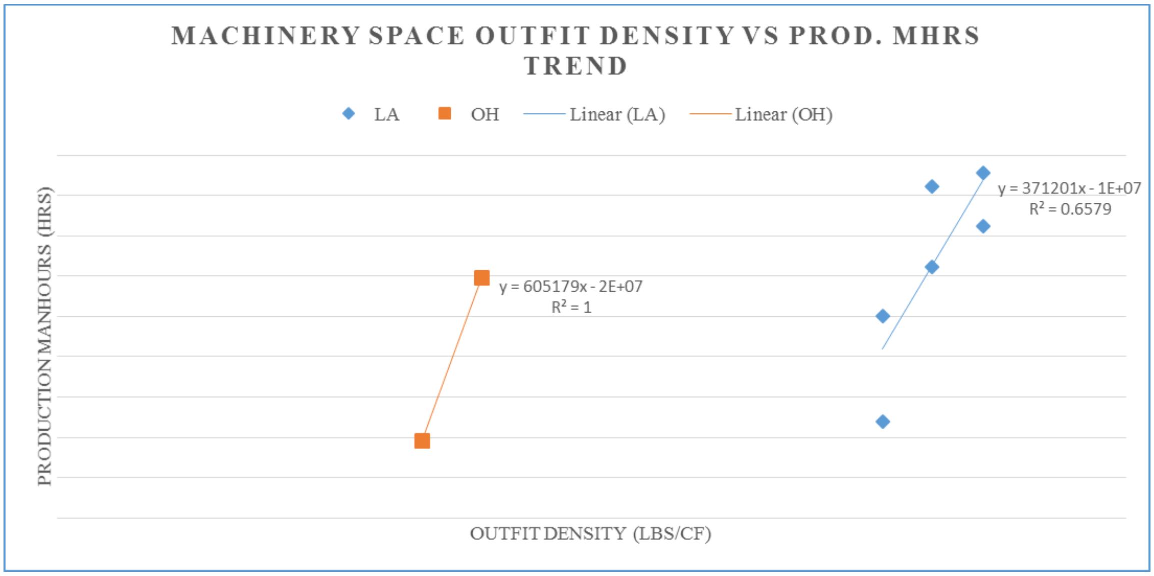

Figure 11. Outfitting density for the machinery space vs production mhrs for LA Class and OH Class.

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IV. RESULTS

Through the analysis, no obvious correlation can be drawn throughout the submarine fleet relating outfitting density to production mhrs. The resultant slope of the increasing trend within *Los Angeles* and *Ohio* classes for both the OPS compartment (Figure 9) and machinery compartments (Figure 11) show that there is a positive correlation between outfitting density and production mhrs. As the compartment becomes more dense (higher outfitting density), the needed production mhrs increases at approximately the rate of the slope. As more *Virginia* class return data is reported from the assembly yard to NAVSEA, the *Virginia* plot can be developed. If the resulting slopes are similar to *Los Angeles,* there may be a correlation that can be applied to a CER for future cost estimates.

For the *Ohio Replacement* program, the OPS compartment outfitting density is on par with the *Seawolf* class outfitting density. The construction methods used to produce *Ohio Replacement* will be similar to the *Virginia* class enabling the shipyards to leverage their learning curves and as many similar components as possible. The projection is that the production mhrs for the OPS compartment will be more than the *Ohio* class, but less than the *Virginia* class. The machinery compartment outfitting density is denser than the *Los Angeles* improved class and less dense than the *Seawolf* class. The expectation based on this analysis would be that there would more production mhrs charged for the machinery compartment of the *Ohio Replacement* class than what was charged for *Los Angeles* class, but less than for the *Seawolf* class.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This analysis investigated the relationship between outfitting density and construction cost through the use of production mhrs. The assumption was that as more components are installed into a limited volume that it would potentially take more production mhrs to complete. The result was a positive correlation between the outfitting density and production mhrs of the OPS and machinery compartments. More data is needed for the *Virginia* class to be able to validate the correlation.

For *Ohio Replacement*, the expected production mhrs/LT will be within 500 mhrs/LT of the fleet mean production mhrs/LT after learning curve. Since the construction method to be used for *Ohio Replacement* is the same as for *Virginia*, and with a philosophy to harness as much of the *Virginia* process and components as possible, the learning curve should be less than for the other classes.

During the modular construction process, the compartment end loading in the production line offers space and access to areas that are not available once the units are loaded and the submarine is fully assembled. For sustainability, removal and reinstallation of interferences and the ability to access certain areas may be seen as an increase to the maintainer mhrs charged. It would be interesting to see how maintenance mhrs have been affected by outfitting density.

B. RECOMMENDATIONS

1. Future Research

While going through the process to create the methodology and analysis for this small scope study, many questions arose that would be beneficial for future research.

a. Outfitting Density Correlation for Maintenance Hours

As mentioned in the conclusion, the rafted compartments and end loading in the production line offers space and access to areas that are not available once the units are loaded and the submarine is fully assembled. This can encourage a behavior to install

components tightly. Removal and reinstallation of interferences and ability to access certain areas in maintenance availabilities could increase maintainer mhrs charged. A correlation could be investigated and aid in formulating mhrs estimates for certain areas of the submarine for maintenance period cost estimate.

b. Compensated Gross Tonnage

Submarine designs are historically evolutionary designs based on the prior class of submarines. To add complexity to an already very densely outfitted design results in a disproportionate increase in construction costs. Compensated Gross Tonnage (CGT) represents the complexity of a vessel design and is a measure of the internal volume of a vessel multiplied by a compensation coefficient (First Marine International 2005). Merchant ships typically use CGT as a factor to define complexity and relate it to cost. Studies have been done for United Kingdom naval vessels by John Cragg, Damien Bloor, Brian Turner and Hamish Bullen and documented in their paper, "Methodology Used to Calculate Naval Compensated Gross Tonnage Factors." Submarine CGTs could be developed to quantify design complexity and understand its potential as a cost driver.

c. Acoustic Requirements and the Effect on Procurement Costs

The demand for acoustic and silencing properties for naval vessels and their components increases with each submarine class to meet the predicted adversary threats. Inside the vessel, everything from pumps to mounting deck structure is affected, as well as quieting material properties that cover the outside of the submarine. It would be of interest to see if a correlation could be investigated between these historical increases in the acoustic requirements and their effect on cost. Survivability/shock requirements could be of similar interest as well.

d. Uncertainty Evaluation of Early Phase Costing Estimates

In the early acquisition phases of concept refinement and technology development/preliminary design, a weight estimate and a costing position are developed for the submarine being designed. Both are built with large assumptions. To understand the uncertainty and potentially draw a quantifiable evaluation that can be used by the

costing community, it would be of interested to compare the return P-5 end cost data back to the costing positions of the two milestone costing positions.

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APPENDIX

The data used for this thesis can be obtained from the following resources:

Weight data from the Final Weight Reports:

> Naval Surface Warfare Center – Carderock Division
> Department 844
> 9500 MacArthur Blvd.
> West Bethesda, MD 20817-5700

End-Cost and Production Man-hour Data:

> Naval Sea Systems Command
> NAVSEA 05C
> 1333 Isaac Hull Avenue, SE
> Washington Navy Yard, DC 20376

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   Monterey, California